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L4	1	(model\$3 near compress\$5) and ((triangle or triangular) near mesh) and (B\$spline near curve)	US-PGPUB; USPAT; EPO; JPO; DERWENT; IBM_TDB	OR	ON	2007/03/29 09:41
L5	23	((triangle or triangular) near mesh) and (B\$spline near curve)	US-PGPUB; USPAT; EPO; JPO; DERWENT; IBM_TDB	OR	ON	2007/03/29 09:41
L6	9	((triangle or triangular) near mesh) and (B\$spline near curve) and compress\$5	US-PGPUB; USPAT; EPO; JPO; DERWENT; IBM_TDB	OR	ON	2007/03/29 09:47
L7	9	((triangle or triangular) near mesh) and (B\$spline near curve) and compress\$5 and (segment\$5 or subdivision)	US-PGPUB; USPAT; EPO; JPO; DERWENT; IBM_TDB	OR	ON	2007/03/29 09:47
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L9	1	((triangle or triangular) near mesh) and (B\$spline near curve) and compress\$5 and (segment\$5 or subdivi\$5) and watershed	US-PGPUB; USPAT; EPO; JPO; DERWENT; IBM_TDB	OR	ON	2007/03/29 09:50
L10	1	((triangle or triangular) near mesh) and (estimat\$4 near curve) and (watershed near (segment\$5 or subdivi\$5))	US-PGPUB; USPAT; EPO; JPO; DERWENT; IBM_TDB	OR	ON	2007/03/29 10:02
L11	2	((triangle or triangular) near mesh) and (estimat\$4 near curv\$5) and (watershed near (segment\$5 or subdivi\$5))	US-PGPUB; USPAT; EPO; JPO; DERWENT; IBM_TDB	OR	ON	2007/03/29 10:03
L12	2	((triangle or triangular) near mesh) and (estimat\$4 with curv\$5) and (watershed near (segment\$5 or subdivi\$5))	US-PGPUB; USPAT; EPO; JPO; DERWENT; IBM_TDB	OR	ON	2007/03/29 10:03

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L13	2	((triangle or triangular) near mesh) and (estimat\$4 with curv\$5) and (watershed with (segment\$5 or subdivi\$5))	US-PGPUB; USPAT; EPO; JPO; DERWENT; IBM_TDB	OR	ON	2007/03/29 10:03
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S12	1	(co\$odinate with ((3D or three\$D or "3"\$dimansional or three\$dimensional) adj object))	US-PGPUB; USPAT; EPO; JPO; DERWENT; IBM_TDB	OR	ON	2007/03/26 09:08
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↑ ABSTRACT

In this paper, a graph partitioning greedy algorithm is presented. This algorithm avoids the hard-constraints of others similar approaches such as the impossibility for some regions to grow after certain step of the algorithm and the uniqueness of the solution. Nevertheless, it allows attaining global results by local approximations using a generalized concept of not over-segmentation, which includes an energy function, and eliminating the not sub-segmentation criterion using a probabilistic criterion similar to that of annealing. The high-variability region problems such as borders are also eliminated identifying them and distributing their pixels among the other neighbor regions. Thus, it is possible to keep the time complexity of usual graph partitioning greedy algorithm and avoiding its high-variability region problems, obtaining better results.

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IEEE TRANSACTIONS ON VISUALIZATION AND COMPUTER GRAPHICS

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Partitioning 3D Surface Meshes Using Watershed Segmentation

 Alan P. Mangan
 Ross T. Whitaker

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Abstract

This paper describes a method for partitioning 3D surface meshes into useful segments. The proposed method generalizes morphological watersheds, an image segmentation technique, to 3D surfaces. This surface segmentation uses the total curvature of the surface as an indication of region boundaries. The surface is segmented into patches, where each patch has a relatively consistent curvature throughout, and is bounded by areas of higher, or drastically different, curvature. This algorithm has applications for a variety of important problems in visualization and geometrical modeling including 3D feature extraction, mesh reduction, texture mapping 3D surfaces, and computer aided design.

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Index Terms- Surfaces, surface segmentation, watershed algorithm, curvature-based methods.

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A hybrid approach to feature segmentation of triangle meshes

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Abstract

Segmentation of a polygonal mesh is a method of breaking the mesh down into ‘meaningful’ connected subsets of meshes called regions or features. Several methods have been proposed in the past and they are either vertex based or edge based. The vertex method used here is based on the *watershed segmentation scheme* which appears prominently in the image segmentation literature and was later applied to the 3D segmentation problem [9 and 10]. Its main drawback is that it is a vertex based method and no hard boundaries (edges) are created for the features or regions. Edge based methods rely on the dihedral angle between polygon faces to determine if the common edge should be classified as a *Feature Edge*. However, this method results in many disconnected edges and thereby incomplete feature loops.

We propose a hybrid method which takes advantage of both methods mentioned earlier and create regions with complete feature loops. Satisfactory results have been achieved for both CAD parts as well as other laser scanned objects such as bones and ceramic vessels.

Author Keywords: Three-dimensional segmentation; Shape recognition; Feature extraction;

Watershed segmentation; Curvature estimation; Triangle mesh

Article Outline

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 - 2.1.1. The no hard boundary problem
 - 2.2. Feature segmentation based on dihedral angle
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 - 3. Hybrid approach
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1. Introduction

The domain of the problem, a triangle mesh (denoted by M^1), consists of a set of n points (vertices $\mathbf{v}_i \in \mathbb{E}^3$; $0 \leq i < n$) and a set of planar convex polygons (faces) made up of these vertices. These are two-dimensional manifolds representing the surface of a three-dimensional object. Triangle meshes are currently a popular surface modeling primitive used extensively to represent real world and synthetic surfaces in computer graphics.

Segmentation means breaking down an existing structure into meaningful, connected subcomponents. In the context of meshes, the sub-components of the structure being broken down are sets of vertices called *regions* which share some ‘commonality’. Mesh segmentation has had numerous applications in the past. Moreover, several existing applications benefit from segmentation. Good examples are feature extraction, decimation, adaptive subdivision [1], and surface fitting for reverse engineering. The motivation for this research was provided by two application domains: optimized triangulated meshes in CAD (Reverse Engineering, Manufacturing, etc.) and over sampled meshes from laser scanned data such as ceramic vessels and bones. Since curvature is not scale invariant, we scale all input files to a unit-bounding box.

2. Related work

We first present two approaches that have been used for segmentation of polygonal meshes and then present our method.

2.1. Vertex based method

A value λ_i could be associated with each vertex \mathbf{v}_i in the data set which somehow

encapsulates the characteristics of the locality of the vertex. The definition of segmentation is the one in which regions consist of connected vertices which have the same λ (within a tolerance). Curvature is selected as the mathematical basis for region separation, i.e. the scalar value λ . Curvature estimation from 3D meshes is dealt with in Hamann [5], Calladine [3] and Kobbelt [8], who extract curvature from a locally fitted quadratic polynomial approximant; and Besl [2], Hoschek [7], and Mangan and Whitaker [9], who describe various discrete curvature approximation schemes. Vertices having the same curvature value would be grouped into regions, separated by vertices with high curvature (which serve as region boundaries). An improved curvature estimation scheme is presented in [10].

The segmentation scheme used is derived from the *Watershed* algorithm for 3D meshes described in [9]. However, there has been considerable research work relevant to this problem based on various other techniques [13, 4, 11, 2 and 6].

Mangan and Whitaker [9] generalize the watershed method to arbitrary meshes by using either the discrete Gaussian curvature or the norm of covariance of adjacent triangle normals at each mesh vertex as the *height field*, analogous to the pixel intensity on an image grid which drives the 2D watershed segmentation algorithm. From our experience, absolute curvature provides the best results for Watershed segmentation [10].

2.1.1. The no hard boundary problem

A major drawback of the vertex-based method is that no hard boundaries are created for the features or regions. Each vertex of an object has its own region information. Therefore, triangles on boundaries have multi-region information. The three vertices of a triangle can be part of three different regions, whereas the triangle itself would be a 'gray' area, i.e. it would not belong to any one region (Fig. 1). Fig. 2(a) shows the boundary triangles in white. This means the regions will not have hard boundaries or edges. This is a known artifact of vertex based Watershed segmentation and is acknowledged in [9]. We call this the *no hard boundary* problem. To solve this problem, we create new triangles by adding midpoints to the edges which have different region labels. Each new vertex contains multiple labels (Fig. 3). This is an extension of the original algorithm [9]. For the selection of the label(s) of a vertex which has multiple labels, the common label of the vertices of the triangle is selected, Fig. 2(b). In Fig. 3(a), there are two possible diagonal splits to make triangles. We select the diagonal which satisfies $\max(\min_{1 \leq i \leq 4} a_i, \min_{1 \leq i \leq 4} b_i)$ where a_i and b_i are interior angles formed by the diagonals, i.e. select the diagonal that results in the best aspect ratio.

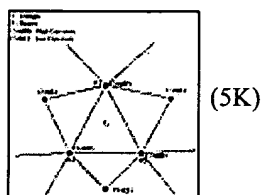


Fig. 1. Shows an example where a triangle T_i will be the gray area, i.e. it will not be part of any region.

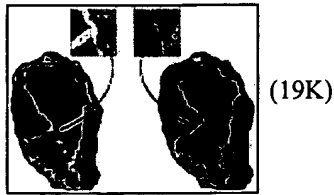


Fig. 2. Segmentation using Watershed method: (a) with no hard boundaries and (b) with boundary solution.

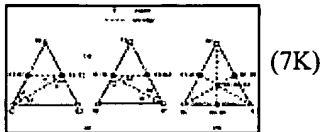


Fig. 3. Creation of triangles on boundaries of an original mesh: (a) for a triangle shared by two regions and (b) for a triangle shared by three regions.

Triangle meshes representing mechanical (CAD) objects are frequently sparse in some areas, with just enough vertices to define each area. This is usually a result of the optimal triangulation from a CAD program or decimation process. In this case, the Watershed method may not segment the object properly or may even lose important regions on the objects. In Fig. 4, the main regions of the object are treated as boundaries because there are not enough vertices in the regions. The boundary solution mentioned earlier will not solve this problem because the method does not create new regions from the boundary regions and the boundary regions will be lost. Moreover, some regions of this object are not segmented properly. This problem is caused by the vertices on feature edges with similar curvatures and those vertices may be treated as the same region. We solve this problem with our proposed approach in Section 3.

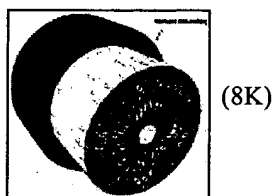


Fig. 4. The mesh segmented using the Watershed method.

2.2. Feature segmentation based on dihedral angle

This method uses an edge-based method for defining feature boundaries. A Feature Edge is defined as follows. *Feature Edge*: An edge shared by two planes whose normal vectors make an angle greater than a certain threshold. The edges obtained are integrated into curves, and

these curves are classified as jump boundaries, folds (roof edges) and ridge lines [12]. Jump boundaries and folds are used to segment the mesh into several regions. The boundary lines are also treated as Feature Edges.

2.2.1. Shortcomings of the method

The main disadvantage of the Feature Edge-based method is that this results in many disconnected Feature Edges and thereby incomplete Feature Loops. Fig. 5 shows this problem. Feature Edges are shown in brown color.

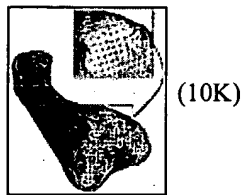


Fig. 5. The feature vertices and edges of the mesh.

3. Hybrid approach

Our proposed method takes advantages of both methods mentioned in the previous sections by using them in conjunction and hence is called the hybrid method. This creates regions with complete Feature Loops. Fig. 7 shows the steps of the Hybrid method. It is described as follows.

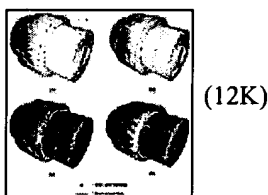


Fig. 7. Various steps of the Hybrid method: (a) original mesh with feature vertices and edges, (b) modified mesh with feature edges and addition of vertices, (c) segmentation using Watershed method, and (d) mesh after deleting additional vertices and triangles.

As explained before, optimally triangulated meshes pose problems for the Watershed segmentation method. To overcome this we identify all the feature edges in the mesh using a threshold (angle). First, we define it as Feature Vertex.

Feature Vertex. Vertices that make up a Feature Edge are defined as Feature Vertices. The reverse is not necessarily true. It is important to note that if both vertices of an edge are Feature Vertices, it does not automatically qualify the edge as a Feature Edge.

Step 1. *Identification of Feature Vertex*. Identify all Feature Vertices based on a threshold angle (dihedral angle) as explained in Section 2.2.

Step 2. *Addition of vertices*. The next step in the process is to add new vertices. Vertices are added to edges of all triangles which have the property that all three vertices are Feature Vertices. See Fig. 6(a). The new vertex is added at the mid point of each edge. We then connect them as shown to create four new triangles. If the triangle has three Feature Edges, then the center point of the triangle is added and six new triangles are created as shown in Fig. 6(b). An addition of vertices requires fixing of the topology as shown in Fig. 6(c). The triangle shown is a neighbor of the triangle to which we added the vertices. This can lead to a hanging vertex problem. To fix this, we connect the new vertex with the vertex on the opposite edge to create two new triangles. As a result of the above, we have two kinds of new vertices; those that lie on the Feature Edges (labeled FV_{high}) and those that do not (labeled as FV_{low}). The reason for labeling is explained below.

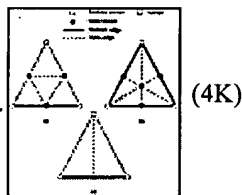


Fig. 6. Creation of triangles on feature edges of an original mesh.

Step 3. *Watershed segmentation*. Next, we apply Watershed segmentation to our modified mesh. We use absolute curvature for our examples. Other curvature estimation methods may be used and their relative merits are explained in [10]. Feature Vertices FV_{high} are assigned the label of maximum curvature. Since they lie on a Feature Edge, assigning them high curvature ensures that a Feature Edge will be preserved as a hard edge. The rest of the vertices in the mesh follow the same procedure as described in the Watershed algorithm for computing curvatures at the vertices. The Feature Vertices contain their own region labels as well as labels of the neighboring vertices. The addition of vertices has an impact on the Descent and Region Merge operations of the Watershed process [9]. This is done to solve the no hard boundary problem which has been described and discussed earlier in this paper.

Step 4. *Removing vertices added in step 2*. To restore the mesh to its original form we must remove the vertices added to the mesh in step 2 earlier. This process restores the topology of the mesh also.

Step 5. *Collating triangles into regions*. The goal of this step is to assign triangles and not vertices to different regions. This is achieved as follows:

Case 1. *All vertices have the same label*. This is simplest of the cases. The triangle is assigned the region label of its vertices.

Case 2. *One vertex has a single label*. This is the case when one vertex has a unique label but the other two vertices have multiple labels. The triangle is assigned the region of the vertex

with single label.

Case 3. Multiple labels but only one common label. The three vertices of the triangle have multiple labels each, however, there is only one label that is common. The triangle is assigned the region label that is common to the vertices in the triangle.

Case 4. All edges are Feature Edges. The triangle qualifies as a region by itself and gets assigned a unique region identifier.

Case 5. Multiple labels and multiple common labels. It is possible that each vertex of a triangle has multiple labels and there is more than one common label. To explain this we will use the example in Fig. 8. Triangle T_1 has vertices with region labels R_1 and R_2 . One of the vertices also has the label R_3 . First, we check if a neighboring triangle shares a Feature edge with T_1 . In this case, we find T_2 shares common Feature edge with T_1 . We then compare the common vertex labels of $T_1(R_1, R_2)$ with common label(s) of $T_2(R_1)$. The label that does not belong to the set of common vertex label(s) of the neighboring triangle is assigned to the targeted triangle (R_2).

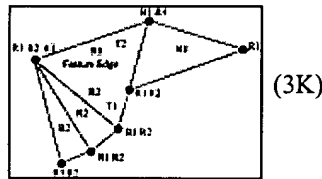


Fig. 8. Assigning regions for case 5, multiple labels with multiple common labels.

If the targeted triangle has more than one feature edge, then the earlier process is repeated for each neighboring triangle that shares a feature edge.² Each such neighbor contributes one or more labels. Then T_1 is assigned the label that is common between the contributed labels.

The targeted triangle may have no feature edge. It means that the triangle is in the same region as the regions of the neighboring triangles. So, the region label of any neighboring triangle is selected as the label of the targeted triangle.

4. Results and conclusions

The hybrid method relies on the Watershed method and additionally uses advantages of the dihedral angle method. The hybrid method does segmentation of smooth objects as well as mechanical objects. It also solves the no hard boundary problem. Fig. 9 shows two mechanical parts. Fig. 9(a) is a gear and Fig. 9(b) is a housing. Fig. 10(a) shows a turbine. Notice that each blade has been segmented into a different region. Fig. 10(b) is a wheel (rim and tire). It is segmented into the following regions, i.e. the tire, rim, bolt holes and a hole for mounting the wheel. These are correctly segmented. All examples are from public domain data sets. Fig. 11 shows the bone data (from Fig. 5) segmented using the hybrid method.

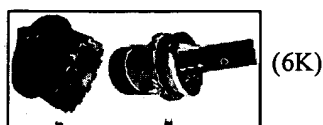


Fig. 9. Segmentations of mechanical parts using the Hybrid method. Threshold for Feature edge: (a) 40° and (b) 30° . Threshold for curvature: both (a) and (b) 0.1. Both parts were scaled to a unit cube.

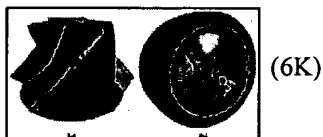


Fig. 10. Segmentation of (a) a turbine and (b) a wheel using the Hybrid method. The threshold for Feature edge: (a) 25° and (b) 30° . Threshold for curvature: both (a) and (b) 0.1. Both parts were scaled to a unit cube.

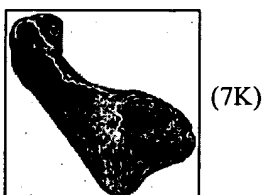


Fig. 11. Segmentation of the bone using the Hybrid method. Threshold for feature edge: 30° , threshold for curvature: 0.12.

We have pointed out the shortcomings of the most popular segmentation approaches for triangle meshes and devised a hybrid method that overcomes these shortcomings. Future work would involve automatic selection of threshold values both for watershed and dihedral angles.

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¹ A mesh consisting of convex polygons can always be converted to a triangle mesh.

² Note that if all three edges are feature edges, then it is dealt under Case 4.

Vitae

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